

Carbon Footprint of Different Harvesting Work Systems in Short Rotation Energy Plantations

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Abstract – Almost half of the total area of Hungary is arable land. Nearly one-third of this area is poor-quality arable land where agriculture would be uneconomical. Energy plantations can be grown extremely well on poor-quality land. Currently, the carbon neutrality of wood as a raw material must also be justified, considering several factors. Environmental life cycle assessment (LCA) was developed as a tool for sustainable, decision-supporting, environmental management, which is an outstanding tool for the well-established analysis of environmental impacts, although the application of it in forestry remained a challenge for the LCA community. No sector specific LCA and life cycle inventory methodology has been developed in forestry; thus, implementing such a methodology remains a big challenge. Calculated on a common functional unit (100 m³/ha wood chips, 100% energy purpose), we have performed a comparative environmental life cycle assessment for harvesting technologies of short rotation energy plantations (technology related to stands of 3 ha of poplar, 5–10 ha of willow, 20 ha of willow), specifically for the third year harvesting work system. Research results on global warming potential show the carbon footprint of harvesting work systems, the knowledge of which has a strong influence on the environmental consideration of raw material (wood chips) and also on the more precise definition of carbon sequestration capacity. The typical values of carbon balance ratio (1.37–1.46) indicate a positive carbon sequestration potential and a magnitude well within the system boundaries of the third year harvesting work system submodule. The results obtained enable the estimation and prediction of environmental impacts for the whole lifecycle of the plantation.

environmental life cycle assessment / carbon footprint / harvesting technologies / global warming potential

Kivonat – Rövid vágásfordulójú energia ültetvények betakarítási munkarendszer változatainak szénlábnyma. Az ország összterületének közel fele szántóföld, melynek közel harmada rossz minőségű szántó, ahol a mezőgazdasági művelés gazdaságtalan. Az energetikai ültetvények a rossz minőségű szántókon kiválóan nevelhetők. A fa, mint nyersanyag szénsemlegessége napjainkban is igazolásra szorul, megannyi tényező figyelembe vételével. A környezeti életciklus-elemzést (LCA) fenntarthatósági, döntéstámogató környezetmenedzsment eszköznek fejlesztették ki, mely kiváló eszköze a környezeti hatások megalapozott vizsgálatának, azonban az erdészeti alkalmazása máig kihívást jelent az LCA közösség számára. Az erdészeti szektorban nincs ágazatspecifikusan kifejlesztett LCA és leltáradat gyűjtési módszertan, melynek megalkotása a legnagyobb kihívások egyike. Kutatásunkban közös funkcionális egységre vetítve (100 m³/ha apríték, 100%-ban energetikai cél), a rövid vágásfordulójú energiaültetvény betakarítási technológiák (3 ha nyár, 5-10 ha fűz, 20 ha fűz állományhoz tartozó technológia) összehasonlító életciklus-elemzésére vállalkoztunk, kifejezetten a 3. éves betakarítási munkarendszer esetén. A globális felmelegedési potenciál eredmények

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rávilágítanak a betakarítási munkarendszerek szénlábnomára, mely ismerete nagyban befolyásolja a nyersanyag (faapríték) környezeti megítélését, valamint a szénmegkötési potenciál pontosabb meghatározását. A szénmérleg viszonyszámának egyes értékei (1,37–1,46) jól mutatják, a 3. éves betakarítási munkarendszer szubmodul rendszerhatárain belül tapasztalt pozitív szénmegkötési potenciált és a nagyságrendet. A kapott eredményekből becsülhetők és előrevetíthetők az ültetvény teljes élettartamának környezeti hatásai.

életciklus-elemzés / szénlábnom / betakarítási technológia / globális felmelegedési potenciál

1 INTRODUCTION

1.1 Life cycle assessment as a decision support tool

There is broad consensus that we must explore and implement methods to minimize resource use in economic and industrial processes while simultaneously reducing the environmental impacts of emissions and waste to near zero. Environmentally sound technologies were identified as a key element to achieving this long-term goal (Heinimann 2012).

In addition to other methods, the environmental life cycle approach, developed from the beginning of the 1990s, is an approach that is able to consider environmental impacts in the whole life cycle of a product or product system from “the cradle to the grave” rather than in one stage only. The bases of this modelling are process approach, environmental inventory, and the application of a specifically developed indicator system. Environmental life cycle assessment (LCA) was developed as a tool for sustainable, decision-supporting, environmental management (ISO 2006a), which is an outstanding tool for the well-established analysis of environmental impacts.

According to Erkman (1997), the concept of industrial ecology encompasses these assessment methods. This aspect scrutinizes industrial systems the same way that ecologists scrutinize ecosystems. The key issues are to model industrial metabolism, map the material and energy flows, and continuously develop environmental performance (Heinimann 2012).

An increasing number of databases and information systems to describe the state of the environment and to trace the environmental impact of individual companies have continuously been created to achieve set environmental protection objectives (Elekné Fodor – Pájer 2017).

Due to their differing intensities, the economic sphere and its open technological processes have dissimilar environmental impacts. Consequently, global environmental problems may occur in different ways due to their corresponding material and energy withdrawals and emissions. An environmental analysis of the technologies through the process and life cycle approach allows for both a detailed analysis and the defining of the contribution to climate change. Changes in the characteristics of environmental elements and systems caused by human activities is called environmental impact. In addition to the changes in growing conditions caused by cultivation techniques and the effects of land cover, the specific environmental aspects of each technology in land uses have to be taken into account. We believe the environmental analysis of technological aspects related to forest use may be an important supplement to current climate research (Polgár et al. 2014). The evaluation of environmental impacts aims to express the significance of the change and, concurrently, prepare development actions and decisions (Polgár – Pájer 2014).

1.2 Life cycle assessment in the forestry sector

Rumpf et al. (2016) states that recognizing the importance of atmospheric carbon sequestration puts forestry in a favourable position. In addition to being nearly carbon neutral, forest management is the only economic activity that allows for the sustained removal of significant amounts of carbon from the atmosphere.

Currently, the carbon neutrality of wood as a raw material must also be justified, taking several factors into account (Klein et al. 2015).

The application of life cycle assessment in forestry has remained a challenge for the LCA community.

Heinimann (2012) and Klein et al. (2015) fully review over twenty years of LCA forestry practice in their work.

The concept of industrial ecology can be traced back to outstanding scholars. The work of Robert Ayres (Ayres – Kneese 1969), Charles Hall (Hall et al. 1979) and Howard T. Odum (Odum et al. 1977) encouraged Professor Ulf Sundberg to carry out preliminary energy analyses regarding forest operations (Sundberg – Svanqvist 1987).

Sundberg (1982) suggests that fuel consumption costs are a key factor in the determination of forest machine operations. Forestry has become completely mechanized, with truck roads, forwarders, and skidders replacing horse-drawn hauling. Berg (1995) stated that the bulk of environmental impacts from forestry operations originates from the significant amounts of fossil fuel required to operate machinery.

Long distance transportation and forest road infrastructure account for about two-thirds of the total impact for typical forest productivity systems (Heinimann – Maeda-Inaba 2004).

Based on the calculations of greenhouse gas (GHG) emissions and energy cycles in the life cycle of wood products, Frühwald – Wegener (1993) concluded that wood could substitute more energy intensive materials possessing higher GHG-burdened footprints during their production and end-of-life stages. Additionally, emissions from fossil resources could be avoided when wood is burned at the end of its life cycle (Frühwald – Wegener 1993).

According to Frühwald (1995), no sector specific LCA and life cycle inventory (LCI) methodology has been developed in the forestry sphere; thus, implementing such a methodology remains a big challenge. According to Heinimann (2012) and Klein et al. (2015), there are currently no significant changes.

Applying sector-LCA in order to achieve both internal (comparative) and external (efficiency enhancing) benefits is a priority according to Frühwald (1995).

Throe – Schweinle (1995) developed a proposal for a standard forestry life cycle model that could serve as a basis for LCA application in forestry.

Based on the review of several LCA studies, Klein et al. (2015) established that great differences existed in the methodological assumptions and their subsequent results. These studies focused on the values of global warming potential (GWP). The term “carbon neutral” is often affixed to raw wood; we propose this term be refined to “low-emission raw material” based on the observed values of GWP (excluding cases where the long-term in situ carbon loss caused by the negative impact of changes in forestry or in the direct or indirect land use).

The surveys examined by the authors focused on spruce, pine, and Douglas fir. Beech, which is an important hardwood in Central Europe, has not yet appeared in European studies.

Due to the favourable ecological environment, “ligneous” biomass has great potential in Hungary. White willow (*Salix alba*) and hybrid poplar (*Populus x euramericana*) can attain higher production, but harvesting technologies have a significant impact on the efficiency of plantations (Dobos et al. 2006).

The model of Klein et al. (2015) represents the basis of life cycle assessment in forest production and creates a proposal for the raw wood process chain.

Raw wood products commonly serve as the base material for other final products; thus, the ecological impacts of raw wood in the forest production system are recognised as only a portion of the total impact. A Belgian study confirmed that despite the relatively low yields, the investigated system on degraded land reached a positive energy balance and can produce 7.9 times more energy than it consumed during rotation (Dillen et al. 2013).

Kim et al. (2016) examined the impact of thinning on the carbon storage of dead organic matter in larch and oak stands. Tellnes et al. (2017) conducted examinations according to carbon footprint calculations of wooden products.

After studying the relevant literature, we can highlight the necessity of a comparative LCA study to fill research gaps, thereby enabling a deeper understanding of the environmental impacts of the harvesting work systems in short rotation energy plantations.

Our goal was to answer the following main research question: what are the typical environmental impacts in short rotation energy plantations of a specific cutting age? Our study objective was to perform a comparative environmental life cycle assessment for the harvesting technologies of short rotation energy plantations (technology related to stands of 3 ha of poplar, 5-10 ha of willow, 20 ha of willow), specifically for the third year (first harvest period) harvesting work system, calculated on a common functional unit (100 m³/ha wood chips, 100% energy purpose). Global warming potential (GWP) should show the carbon footprint of harvesting work systems, the knowledge of which has a strong influence on the environmental consideration of raw material (wood chips) and on the more precise definition of carbon sequestration capacity. The results obtained in the third year enable the estimation and prediction of environmental impacts for the whole lifecycle of the typical plantation.

2 MATERIALS AND METHODS

We carried out our fieldwork in short rotation hybrid poplar and willow energy plantations in Hungary, which were planted in single or twin rows. We separated the harvesting work systems of plantations based on the categories of the area, which are the following: large (above 20 ha), medium (5 to 10 ha) and small (below 3 ha).

The plantations are harvested 3 to 5 times by a return period of 3 to 5 years depending on site conditions and tree species. The goal of our study was to determine the common resulting environmental impacts of the harvesting work system in the cutting age of 3 years by using the life cycle assessment method.

In our study, we analysed the most ideal conditions of mechanisation. A wide range of other applicable solutions besides the work systems described below exists for the three area categories.

Short rotation energy plantation of 20 ha or more:

In the case of large plantation areas, the application of high performance machines is more favourable economically. A single machine, the so-called self-propelled walking chipper, executes the felling of individual trees of the plantation (felling), places the felled trees into a chipping chamber, chips the felled trees, and loads the wood chips onto the forwarder. Delivery equipment, more specifically tractors and trailers, forward the wood chips onto the loader and complete the unloading (dumping). A front loader then loads the wood chips onto the transporting truck (tractor with semi-trailer) (*Figure 1-2*).



Figure 1-2. Large-plantation harvesting technology for a plantation of 20 ha or more (Photo: Vinkovics, S., Horváth, A. L.)

Short rotation energy plantation of 5-10 ha

Self-propelled walking chippers are not economically viable for the harvesting of medium plantations. In this case, it is better to apply a walking chipper that can be connected to a power tool as an adapter. In this way, the basic machine can also be used for other functions in addition to harvesting operations. The felling, chipping, and loading onto the forwarder all occur within a single operation in this case. As mentioned in the previous category, a tractor-trailer combination also completes the forwarding here, while a crane truck loads and transports the wood chips. (Figure 3-4).



Figure 3-4. Medium-plantation harvesting technology for a plantation of 5-10 ha (Photo: Vinkovics, S., Horváth, A. L.)

Short rotation energy plantation below 3 ha

In the case of small energy plantations, manual power tools and low-power machines are optimal. A motor chainsaw or clearing saw is appropriate to fell individual trees. A mobile chipper operated by a crane power tool can carry out wood chipping for trees felled in the same direction. Once again, a tractor with a trailer is the most suitable machine to forward wood chips. A crane truck is the most effective equipment for loading and transport (Figure 5-6).



Figure 5-6. Small-plantation harvesting technology for a plantation below 3 ha (Photo: Röchricht, H., Horváth, A. L.)

The methodology applied corresponds to the requirements of the ISO 14040:2006 (ISO 2006a) and ISO 14044:2006 (ISO 2006b) standards. The analysis was completed using GaBi thinkstep software (GaBi thinkstep 2018). We focused on the carbon footprint (GWP 100 years) from impact assessment results. Describing the climate change contribution by analysing the technological carbon footprint (GWP) helps to understand the environmental impact of raw wood products (wood chips).

Interpretation of carbon footprint

The carbon footprint (considered greenhouse gas emissions to air only) resulting from harvesting technologies should be interpreted as an absolute value in our studies (hereinafter referred to as carbon footprint) because of the contained fossil CO₂ emissions and also the amount of biotic-origin (neutral) CO₂ emissions resulting from the firing of typical amounts of wood chips (absolute dry).

This explanation of this carbon footprint is justified because the first commitment period of the Kyoto Protocol had not yet permitted the consideration of harvesting for industrial use as carbon capture; instead, all types of harvesting needed to be considered collectively as carbon emissions (Führer – Mátyás 2005). However, progress was made in the second commitment period of the protocol, and the carbon storage function of wood products can now be included in calculations (Frieden et al. 2012). In our case, the timber is 100% utilized as wood chips for energy purposes; therefore, the above interpretation and the carbon storage function of wood products are irrelevant.

In addition, the burning of firewood has a solid ash output as well, which must be considered as a carbon pool in our system.

Breeding and selection for SRC (Short Rotation Coppice) are complex; exceeding the fast growth rates is not the only aim. The main goal of the current study is to quantify the amount of CO₂ emitted for a certain amount of energy generated. The next step is to compare the amount of CO₂ emitted to generate the same amount of energy from a non-renewable source. The final step is the calculation of a whole LCA for harvesting

3 STEPS OF THE LCA

Corresponding to the ISO 14040:2006 standard (ISO 2006a), we followed the main steps of LCA: goal and scope definition; life cycle inventory analysis; impact assessment and interpretation.

3.1 Goal and scope definition

We conducted assessments in one-row or twin-row planting short rotation energy plantations (willow and poplar).

Goal

We performed the comparative life cycle assessment (LCA) for the studied harvesting work system technologies at the cutting age of 3 years in order to rank them based on carbon footprint (CF-carbon footprint/carbon profile). By the LCA method, we have performed the environmental impact assessment concerning the studied technologies.

System boundaries

The system boundaries determined in technologies: work in felling area – forest and road transport - firing of wood chips (energy goal).

We considered the environmental impacts of fuel and lubricating oil production in our model. The total amount of harvested wood will be used as wood chips for energy goals.

Further use of wood is not included in the studies. In addition, the environmental parameters in the production of machines and tools necessary in the technologies, the impacts of building forest roads, and changes in land use are also not included in the analysis.

Processes involved

In the case of short rotation energy plantations (willow and poplar stands): felling (in 3 ha poplar stand only); chipping with chipper (in 3 ha poplar stand only)/mobile chipper; forwarding, loading with crane truck / with front loader (in 20 ha poplar or willow stand only) + transport with crane truck / with trailer truck (in 20 ha poplar or willow stand only) + unloading with crane truck; firing of wood chips (absolute dry, energy goal).

The transport distance was considered uniformly as 40 tonne kilometre [tkm].

Functional unit and reference flow

As a functional unit, 1 ha of stand affected by technology was considered by the harvesting life cycle. As reference flow 100 m³ of standing wood before cutting (100% energy goal) per 1 ha was considered.

3.2 Life cycle inventory analysis

We established an environmental inventory database (input- output, elementary flow) for the examined optimum technologies. We also worked with standard data, which often contains errors; nevertheless, their application was indispensable for the analysis.

The data reference period was the winter of 2015/2016. The geographical validity of the data is national. The data sources stem from our own data, expert estimations, and published data.

We have established the typical ecobalance for each stand (based on data from verified experts). Thereafter, we prepared the life cycle model of the examined technologies.

3.3 Impact assessment and interpretation

The methodology steps of the impact assessment are described in the ISO 14044:2006 (ISO 2006b) standard.

According to Simon (2012), the CML 2001 (Guinée et al. 2002) characterization factor for the major emissions of “GWP 100 years” is well suited to the IPCC 2007 study. The method is suitable for carbon footprint (CF) calculations.

We verified the results of life cycle inventory and impact assessment in the last phase of the LCA; furthermore, we established our conclusions. We focused on the carbon footprint.

We displayed the percent values of life cycle contribution of each impact category. Based on the values obtained, we set up the increasing environmental ranking of technologies. This resulted in the carbon footprint environmental impact assessment related to the technologies.

In order to normalize the carbon footprint values for the carbon sequestration of timber, we set up stand-specific ratios.

4 RESULTS

4.1 Inventory analysis

According to the processes, we have summarized the data of both the input and output sides in tabular form (*Table 1*).

Table 1. Total input and output environmental inventory data of harvesting work systems per 1 ha of short rotation energy plantations in 2015-2016, winter in the third-year stand age per 100 m³ standing wood for cutting (Hungary)

Parameter	Unit	Harvesting work system		
		3 ha > hybrid poplar stand	5–10 ha hybrid poplar or willow stand	20 ha < hybrid poplar or willow stand
Input				
Fuel	kg	592	558	225
Lubricating oil	kg	55	31	18
Output				
CO ₂ emission from fuel	kg	1,870	1,740	697
CO ₂ emission from firewood and slash burning	kg	58,903	59,800	59,800
Total CO ₂ emission	kg	60,773	61,541	60,497
Waste oil (recycled)	kg	46	31	17

We considered the data in the reference period of 2015–2016, winter in the third-year stand age per 100 m³ standing wood for cutting (Hungary).

On the input side, fuel need and the use of lubricating oil for the machines are significant, while on the output side, the emission of CO₂ and waste sump oil (recycled) turned out to be significant. In our case, the timber is 100% utilized as wood chips for energy purposes. We considered the CO₂ emissions from fuel and from firewood and slash burning as well. The amount of CO₂ emissions from firewood and slash burning is nearly three times higher than the amount of CO₂ emission from fuel.

4.2 Impact assessment

In the following (Table 2), we focused exclusively on the results of the CML 2001 (April 2015) method being sufficient for characterization.

Table 2. Profile of environmental impacts of work systems by impact categories of CML 2001 (April 2015)

CML2001 (April 2015) Impact Categories	Harvesting work system		
	3 ha > hybrid poplar stand	5–10 ha hybrid poplar or willow stand	20 ha < hybrid poplar or willow stand
Abiotic Depletion (ADP elements) [kg Sb-Equiv.]	1.15E-04	1.05E-04	4.32E-05
Abiotic Depletion (ADP fossil) [MJ]	30,853.98	28,031.50	11,568.25
Acidification Potential (AP) [kg SO ₂ -Equiv.]	1.96	1.78	0.74
Eutrophication Potential (EP) [kg Phosphate-Equiv.]	0.58	0.54	0.22
Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB-Equiv.]	20.14	18.58	7.59
Global Warming Potential (GWP 100 years) [kg CO ₂ -Equiv.]	61,003.29	61,735.45	60,581.02
Global Warming Potential (GWP 100 years), excl biogenic carbon [kg CO ₂ -Equiv.]	61,145.29	61,869.36	60,635.01
Human Toxicity Potential (HTP inf.) [kg DCB-Equiv.]	86.71	79.77	32.66
Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB-Equiv.]	37,045.95	33,506.34	13,867.13
Ozone Layer Depletion Potential (ODP, steady state) [kg R11-Equiv.]	3.23E-09	2.78E-09	1.19E-09
Photochem. Ozone Creation Potential (POCP) [kg Ethene-Equiv.]	0.23	0.22	0.09
Terrestrial Ecotoxicity Potential (TETP inf.) [kg DCB-Equiv.]	28.29	26.66	10.75

Work systems had the greatest impact on global warming (GWP 100 years) throughout their life cycle. This can be explained by the amount of carbon dioxide the technologies released into the atmosphere from the fuel used. Significant impact categories emerged, namely the abiotic

depletion potential (ADP foss) as well as the marine aquatic ecotoxicity potential (MAETP). These categories can be explained by the contribution of fuel and lubricant inputs.

According to the system boundaries, we did not get any significant effects in the impact categories of acidification potential (AP), eutrophication potential (EP), freshwater aquatic ecotoxicity potential (FAETP inf.), human toxicity potential (HTP inf.), photochemical ozone creation potential (POCP) and terrestrial ecotoxicity potential (TETP inf.).

4.3 Impact interpretation. Carbon footprint calculation. Technology ranking, impact rating of technologies

Based on the carbon footprint impact category, we set up a technology ranking to attain the environmental impact rating of technologies based on absolute carbon footprint. The ranking is presented in the below table (Table 3).

Among the examined system boundaries, we demonstrate the carbon footprint development according to the CML2001 method.

Table 3. Life cycle contribution (%) and carbon footprint-based (absolute, incl. biotic CO₂) ranking of the certain harvesting technologies. Life cycle contribution of certain harvesting work systems according to the carbon footprint (absolute, incl. biotic CO₂) of the wood fired and the technological processes (per 100 m³/ha stand in Hungary)

Carbon footprint (CF)	Harvesting work system	Whole technology rotation carbon footprint			Burning of wood chips (incl biological) carbon footprint			Technological processes carbon footprint	
		[kg CO ₂ -Equiv.],		%	[kg CO ₂ -Equiv.],		%	[kg CO ₂ -Equiv.],	
		%	biotic+fossil		%	biotic		%	fossil
CML2001 - Apr. 2015, Global Warming Potential (GWP 100 years) [kg CO ₂ -Equiv.]	20 ha < poplar or willow	33	60,581	100	59,800	99	781	1	
	3 ha > poplar	33	61,003	100	58,903	97	2,100	3	
	5-10 ha poplar or willow	34	61,735	100	59,800	97	1,935	3	

In the final result, short rotation energy plantations presented almost equal absolute carbon footprint values, regardless of the different technologies applied in the typical stands.

Carbon footprint-based ranking of harvesting work systems:

- On the basis of absolute carbon footprint (considered fossil and biotic origin together), the ranking of harvesting work systems is the following: “20 ha < poplar or willow (33%) – 3 ha > poplar (33 %) – 5-10 ha poplar or willow (34%)”.
- Based on absolute carbon footprint, the ranking of technologies in the whole technology rotation is the following: “20 ha < poplar or willow (60,581) – 3 ha > poplar (61,003) – 5-10 ha poplar or willow (61,735)” (in the values of GWP 100 years [kg CO₂-Equiv.]).
- When considering the clearly fossil carbon footprint of technological processes, the ranking of “20 ha < poplar or willow (781) – 5-10 ha poplar or willow (1,935) – 3 ha > poplar (2,100)” (in the values of GWP 100 years [kg CO₂-Equiv.]) resulted.

CO₂ emissions of biotic origin resulting from wood firing has a major influence on the carbon footprint of total life cycle (97-99%), and the same ranking of stands can be observed in every case.

The following figure illustrates the contribution of processes to CO₂ emissions in fossil dimension (Figure 7).

In the 3 ha> poplar and in the 5-10 ha poplar or willow stands we found that 20-30% of fossil CO₂ emissions are caused by the work in the felling area, while 70-80% are due to the loading, transport, and unloading of wood. In the technology processes of the 20 ha< poplar stand the distribution is 50-50%.

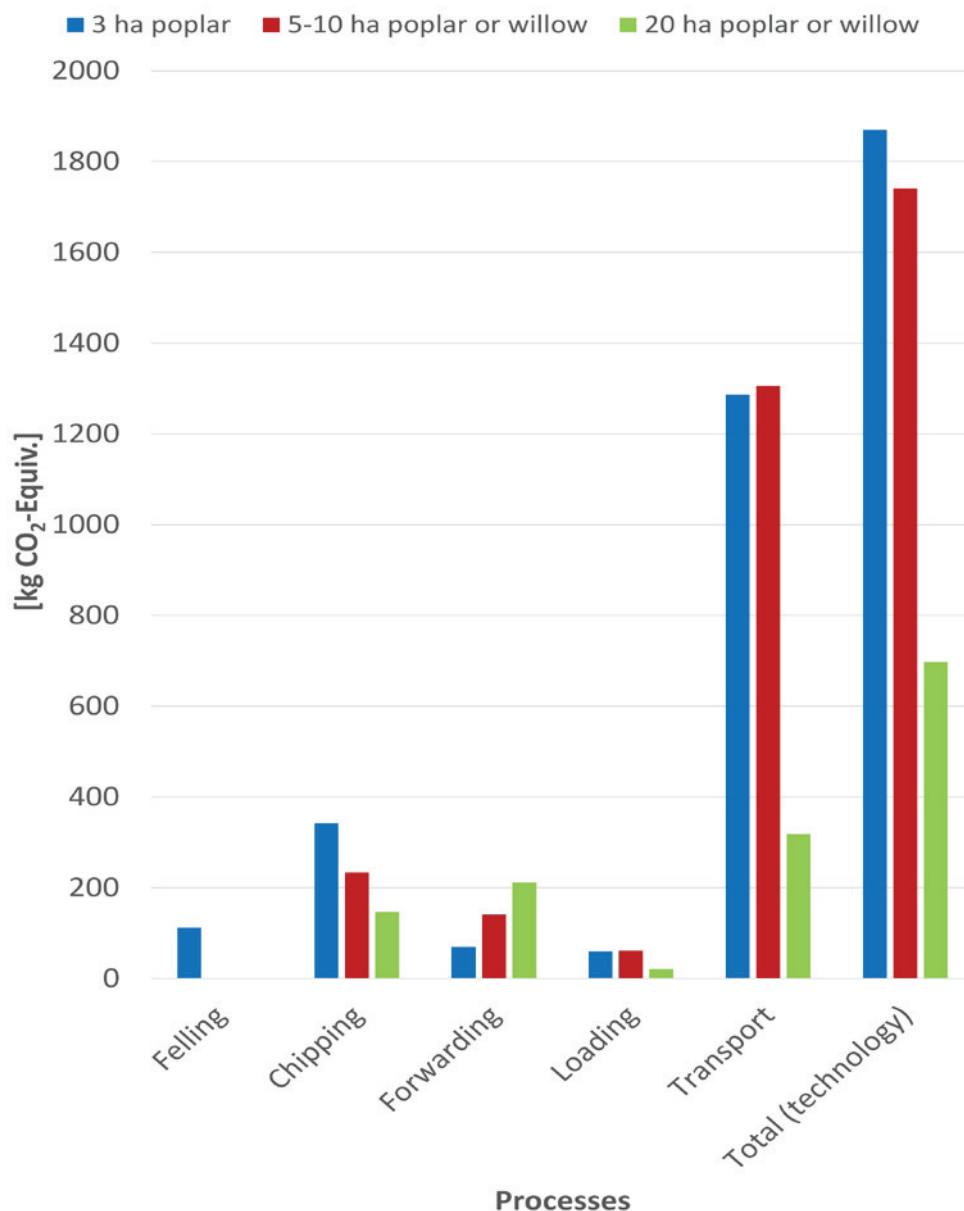


Figure 7. Contribution of processes to CO₂ emissions in fossil dimension of carbon footprint

In order to normalize the carbon footprint values (Table 3) for the carbon sequestration of timber, we set up stand-specific ratios (Table 4). Based on the amount of cut wood at the cutting age of 3 years, the appropriate carbon footprint values [kg CO₂-Equiv.] were related to the carbon-dioxide need sequestered from the atmosphere [kg CO₂/ha] (Buzás 2005) according to the carbon storage of this wood amount typical for the different tree species (Vadász 1924, Ákos 1964). By these means, we have given the carbon sequestration potential.

Table 4. Life cycle contribution of certain harvesting work systems according to the carbon footprint (absolute, incl. biotic CO₂) of the wood chips fired and the technological processes vs. carbon sequestration of cut wood according to the whole technological rotation

Carbon footprint (CF)	Harvesting work system	Standing wood for cutting in the whole technology rotation [m ³ /ha]	A	A/B	A/C	A/D
CML2001 - Apr. 2015, Global Warming Potential (GWP 100 years) [kg CO ₂ -Equiv.]	20 ha< poplar or willow	100	88,476	1.46	1.48	113.28
	3 ha> poplar	100	83,743	1.37	1.42	39.87
	5-10 ha poplar or willow	100	88,476	1.43	1.48	45.71

Abbrev.: A-CO₂ need from the atmosphere sequestered by the stand (cut wood) (Buzás 2005) necessary for the carbon storage of the given tree species (Vadász 1924, Ákos 1964) [kg CO₂/ha]; B-Whole technology rotation carbon footprint (Table 3) [kg CO₂-Equiv.]; C-Burning and biological burning of firewood and slash carbon footprint (Table 3) [kg CO₂-Equiv.]; D-Technological processes carbon footprint (Table 3) [kg CO₂-Equiv.]

The development of the ratio is between 1.37-1.48 for the carbon footprint for all of the technology (absolute carbon footprint) and the burning of wood chips (biotic dimension): “3 ha > poplar (1.37) – 5-10 ha poplar or willow (1.43) – 20 ha < poplar or willow (1.46)”.

This ratio was 39.87-113.28 for the carbon footprint of technological processes (fossil dimension): „3 ha > poplar (39.87) – 5-10 ha poplar or willow (45.71) – 20 ha < poplar or willow (113.28)”.

In the system boundaries of the harvesting life cycle stage at the cutting age of 3 years, the ratio values indicate the positive carbon sequestration potential and magnitude well, experienced both in absolute value and by dimension.

It should be emphasized that the burning of firewood has a solid ash output as well, which must be considered as a carbon pool of the system. Ash is largely responsible for the above-mentioned positive characteristic of the carbon sequestration of the system.

At the forest production stage of the raw wood process chain, our estimate verifies the statement of Klein et al. (2015), according to which wood is a low-emission raw material. Based on the environmental impacts studied at this harvesting stage, the positive carbon sequestration potential of the whole life cycle can be premised relative to the ratios.

Within the examined system boundaries, the environmental indicators are more favourable in the case of harvesting work systems related to the larger area category than to work systems related to the small area category.

5 DISCUSSION AND CONCLUSIONS

Applying sector-LCA in order to achieve both internal (comparative) and external (efficiency enhancing) benefits is a priority. After studying the relevant literature, we can highlight the necessity of a comparative LCA study to fill research gaps, thereby enabling a deeper understanding of the environmental impacts on short rotation energy plantations. Calculated on a common functional unit (1 ha), we have performed a comparative environmental life cycle assessment for harvesting work systems at the cutting age of 3 years in plantations: large: 20 ha< poplar or willow; medium: 5-10 ha poplar or willow; small: 3 ha> poplar.

We compared and ranked the optimum harvesting technologies at the cutting age of 3 years in the different area-based categories from an environmental perspective based on their carbon footprints.

We created an optimum environmental inventory database typical for the stands according to harvesting work system at the cutting age of 3 years life cycle stage. On the input side, fuel need and the use of lubricating oil for the machines are considerable, while on the output side, the emission of CO₂ and waste sump oil (recycled) turned out to be significant.

We found that felling area work causes 30-40% of fossil CO₂ emissions, while the remaining 60-70% are due to the loading, transport, and unloading of wood.

We built up the life cycle models of technologies using GaBi thinkstep software and, subsequently, we performed impact assessments. The technologies used in forestry had the largest contribution to the impact category of global warming (GWP). Significant impact categories emerged, namely the abiotic depletion potential (ADP foss) as well as the marine aquatic ecotoxicity potential (MAETP).

Based on their carbon footprint, we compared and ranked the typical harvesting technologies in terms of environmental impact, according to the whole technology.

When the values of carbon footprint contribution in the harvesting work systems are expressed in percentage terms, an increasing technological ranking of “20 ha < poplar or willow (33%) – 3 ha > poplar (33 %) – 5-10 ha poplar or willow (34%)” emerged. Based on absolute carbon footprint, the ranking of stands in the whole life cycle is the following: “20 ha < poplar or willow (60,581) – 3 ha > poplar (61,003) – 5-10 ha poplar or willow (61,735)” (in the values of GWP 100 years [kg CO₂-Equiv.]). When considering the clearly fossil carbon footprint of technological processes, the ranking of “20 ha < poplar or willow (781) – 5-10 ha poplar or willow (1,935) – 3 ha > poplar (2,100)” (in the values of GWP 100 years [kg CO₂-Equiv.]) resulted in the whole life cycle.

In order to illustrate the extent of the carbon footprint, we used the estimated carbon sequestration of stands. We set up stand-specific ratios whose values (1.37-1.48) are good indicators of the positive balance: „3 ha > poplar (1.37) – 5-10 ha poplar or willow (1.43) – 20 ha < poplar or willow (1.46)”. The solid output of firewood burning, wood ash, as a carbon pool, is largely responsible for the above-mentioned positive character of carbon sequestration of the system.

The study results (GWP) highlight the carbon footprint of harvesting processes. Knowledge of these has a strong influence on the consideration of raw wood products (wood chips) as low-emission raw materials, and on the more exact definition of carbon sequestration capacity. This information will also help to better assess climate risks and climate change. The results obtained enable the estimation and prediction of environmental impacts for the whole lifecycle of the plantation.

Results are based on optimum environmental inventory data and should be interpreted in the domestic context. Following the introduced steps, this methodology can be adapted for other countries, applying region specific data. Outcome of the research are comparable with other LCA studies only in the case of the same functional unit and system boundaries. A better understanding of environmental impacts can be improved by the extension of system boundaries and inventories and the involvement of further primary and secondary processes.

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REFERENCES

- ÁKOS, L. (1964): Erdészeti, vadászati, faipari lexicon. [Forestry, Hunting, Wood Technology Lexicon.] Mezőgazdasági Kiadó, Budapest, Hungary. (in Hungarian)
- AYRES, R.U. – KNEESE, A.V. (1969): Production, consumption and externalities. *The American Economic Review* 59 (3): 282–297. https://doi.org/10.1007/978-3-642-27922-5_24
- BERG, S. (1995): The Environmental Loads of Fossil Fuels in Swedish Forestry – an Inventory for a LCA. In: *Life-Cycle Analysis – a Challenge for Forestry and Forest Industry*. EFI Proceedings No. 8 (Frühwald, A. – Solberg, B. (eds.)), European Forest Institute, Hamburg, Germany 3-5 May 1995. 57–68.
- BUZÁS, Z. (2005): Buzás Zoltán számítása az Sz. közelében lévő Mátrakeresztes erdőtag CO₂ lekötésének évi értékére [The Calculation of the Carbon Sequestration / year of Municipal Forest Area Mátrakeresztes Near to Sz. by Zoltán Buzás]. Web site [online 27 December 2017], URL: http://www.fagosz.hu/fataj/FATAJ_online/2006/08_02200226/Kyoto/Buzas_SZ-xx-erdotag-szamitasa.pdf (in Hungarian)
- DILLEN, S.Y. – DJOMO, S.N. – AL AFAS, N. – VANBEVEREN, S. – CEULEMANS, R. (2013): Biomass yield and energy balance of a short-rotation poplar coppice with multiple clones on degraded land during 16 years. *Biomass and Bioenergy* 56: 157–165. <https://doi.org/10.1016/j.biombioe.2013.04.019>
- DOBOS, A. – MEGYES, A. – SÜLYÖK, D. (2006): Fás szárú növények energetikai célú hasznosításának lehetőségei a Nyírbátori kistérségben [Possibilities for utilization of woody plants for energy goal in the Nyírbátor micro-region]. *Debreceni Egyetem [University of Debrecen]*, Debrecen, Hungary (in Hungarian)
- ELEKNÉ FODOR, V. – PÁJER, J. (2017): Application of Environmental Information Systems in Environmental Impact Assessment (in Hungarian). *Acta Silvatica et Lignaria Hungarica* 13 (1): 55–67. <https://doi.org/10.1515/aslh-2017-0004>
- ERKMAN, S. (1997): Industrial ecology: an historical view. *Journal of Cleaner Production* 5 (1): 1–10.
- FRIEDEN, D – PENA, N. – BIRD, D.N. (2012): Incentives for the use of forest biomass: A comparative analysis of Kyoto Protocol accounting pre- and post-2012. *Smart Forests* 4: 84–92. <https://doi.org/10.1080/20430779.2012.723513>
- FRÜHWALD, A. (1995): LCA – a Challenge for Forestry and Forest Product Industry. In: *Life-Cycle Analysis – a Challenge for Forestry and Forest Industry*. EFI Proceedings No. 8 (Frühwald, A. – Solberg, B. (eds.)). European Forest Institute, Hamburg, Germany, 3-5 May 1995. 10–11.
- FRÜHWALD, A. – WEGENER, G. (1993): Energiekreislauf Holz- ein Vorbild für die Zukunft [Energy cycle wood - a role model for the future]. *HOLZ- Erzeugung und Verwendung-Ein Kreislauf der Natur [WOOD Production and Use-A cycle of nature]*. Dreiländer-Holztagung in Garmisch-Partenkirchen [Three countries wood conference in Garmisch-Partenkirchen] 15: 49–60. (in German)
- FÜHRER, E. – MÁTYÁS, CS. (2005): Erdőgazdálkodás és klímabizonytalanság [Forestry Management and Climate Uncertainty]. *AGRO-21 füzetek [AGRO-21 Booklets]* 41: 124–128. (in Hungarian)
- GABI THINKSTEP (2018): GaBi Professional, Thinkstep, Leinfelden-Echterdingen, Germany. Web site [online 3 December 2018], URL: <https://thinkstep.com/software/gabi-software/gabi-professional>.
- GUINÉE, J.B. – GORRÉE, M. – HEIJUNGS, R. – HUPPES, G. – KLEIJN, R. – KONING, A. DE – OERS, L. VAN – WEGENER SLEESWIJK, A. – SUH, S. – UDO DE HAES, H.A. – BRUIJN, H. DE – DUIN, R. VAN – HUIJBREGTS, M.A.J. (2002): CML 2001. Handbook on life cycle assessment. Operational guide to the ISO standards. I: LCA in perspective. IIa: Guide. IIb: Operational annex. III: Scientific background. Kluwer Academic Publishers, Dordrecht, The Netherlands. 692 p.
- HALL, C. – LAVINE, M. – SLOANE, J. (1979): Efficiency of energy delivery systems: I. An economic and energy analysis. *Environmental Management* 3 (6): 493–504. <https://doi.org/10.1007/BF01866318>

- HEINIMANN, H.R. (2012): Life Cycle Assessment (LCA) in Forestry – State and Perspectives. *Croatian Journal of Forest Engineering (CROJFE)* 33 (2): 357–372.
- HEINIMANN, H.R. – MAEDA-INABA, S. (2004): Environmental Performance Indicators EPIs for Forest Roads Network Systems. In: 2004 International Mountain Logging Conference. A Joint FERIC, UBC and IUFRO d3 Conference (Heidin, I.D. – Krag, R. (eds.)). Published on CD. Forest Engineering Research Institute of Canada, FERIC, Vancouver, BC, Canada 2004. 1–13.
- ISO (2006a): ISO 14040:2006. Environmental management. Life cycle assessment. Principles and framework (ISO 14040:2006). International Organization for Standardization, Geneva, Switzerland. 20 p.
- ISO (2006b): ISO 14044:2006. Environmental management. Life cycle assessment. Requirements and guidelines (ISO 14044:2006). International Organization for Standardization, Geneva, Switzerland. 46 p.
- KIM, S. – HAN, S.H. – LEE, J. – KIM, C. – LEE, S-T. – SON, Y. (2016): Impact of thinning on carbon storage of dead organic matter across larch and oak stands in South Korea. *iForest Biogeosciences and Forestry* 9: 593–598. <https://doi.org/10.3832/ifor1776-008>
- KLEIN, D. – WOLF, C. – SCHULZ, C. – WEBER-BLASCHKE, G. (2015): 20 years of life cycle assessment (LCA) in the forestry sector: state of the art and a methodical proposal for the LCA of forest production. *Int J Life Cycle Assess*, Springer-Verlag, Berlin Heidelberg 20 (4): 556–575. <https://doi.org/10.1007/s11367-015-0847-1>
- ODUM, H.T. – KEMP, W. – SELL, M. – BOYNTON, W. – LEHMAN, M. (1977): Energy analysis and the coupling of man and estuaries. *Environmental Management* 1 (4): 297–315.
- POLGÁR, A. – PÁJER, J. (2014): Enhancement of the Corporate Environmental Performance. *Acta Silvatica et Lignaria Hungarica* 10 (1): 49–64. <https://doi.org/10.2478/aslh-2014-0004>
- POLGÁR, A. – PÉCSINGER, J. – PINTÉRNÉ NAGY, E. – ELEKNÉ FODOR, V. – RUMPF, J. – SZAKÁLOSNE MÁTYÁS, K. – HORVÁTH, A. – BAZSÓ, T. (2014): Forestry and Field Plant Production Technologies in Environmental Life-Cycle Thinking. In Santamarta, J. C. – Hernández-Gutiérrez, L. E. – Arraiza, M. P. (eds.): *Natural Hazards & Climate Change / Riesgos Naturales y Cambio Climático*. Colegio de Ingenieros de Montes/Forestry Engineers Association, Madrid, Spain ISBN: 978-84-617-1060-7. pp. 155–174.
- RUMPF, J. – HORVÁTH, A.L. – MAJOR, T. – SZAKÁLOSNE MÁTYÁS, K. (2016): Erdőhasználat [Forest Utilization]. Mezőgazda Kiadó [Agriculture Publishing House], Budapest, Hungary. (in Hungarian)
- SIMON, B. (2012): A rendszerhatárok és a hatásvizsgálati módszer megválasztásának szerepe az LCA eredményében – az elektromos-energia előállítás példáján keresztül [The role of selection of system boundaries and impact assessment method in results of LCA – illustrated by the production of electricity]. *Eco-matrix, LCA Center - Magyar Életciklus Elemzők Szakmai Egyesület On-line folyóirata* [Eco-matrix. On-line magazine of the LCA Center – Professional Association of Hungarian Life Cycle Analysts]. 2012 (1-2): 11–24. (in Hungarian)
- SUNDBERG, U. (1982): A study on cost of machine use in forestry – Proposing fuel consumption as cost determinant. The Swedish University of Agricultural Sciences. Department of Operational Efficiency. Report No. 142, Upsala, Sweden. 89 p.
- SUNDBERG, U. – SVANQVIST, N. (1987): Fuel consumption as indicator of the economics of mechanization. *Scandinavian Journal of Forest Research* 2 (1-4): 389–398.
- TELLNES, L.G.F. – GANNE-CHEDEVILLE, C. – DIAS, A. – DOLEZAL, F. – HILL, C. – ZEA ESCAMILLA, E. (2017): Comparative assessment for biogenic carbon accounting methods in carbon footprint of products: a review study for construction materials based on forest products. *iForest Biogeosciences and Forestry* 10: 815–823. <https://doi.org/10.3832/ifor2386-010>
- THOROE, C. – SCHWEINLE, J. (1995): Life Cycle Analysis in Forestry. In: *Life-Cycle Analysis – a Challenge for Forestry and Forest Industry*. EFI Proceedings No. 8 (Frühwald, A. – Solberg, B. (eds.)). European Forest Institute, Hamburg, Germany 3-5 May 1995. 15–16.
- VADÁSZ, E. (1924): A szén és petróleum múltja és jövője [The past and future of coal and petroleum]. Athenaeum Kiadó [Athenaeum Publishing House], Budapest, Hungary. Web site [online 27 December 2017], URL: <http://mek.oszk.hu/02200/02232/html/#4>. (in Hungarian)